METABOLICALLY CONSISTENT BREATHING RATES FOR USE IN DOSE ASSESSMENTS

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Abstract—**Assessments of doses resulting from exposures to airborne gases and particles are based almost exclusively on inhalation rates that are inconsistent with the quantities of oxygen needed to metabolize dietary intakes of fats, carbohydrates, and protein. This inconsistency leads to erroneous estimates of inhalation exposures and can distort the relative importance of inhalation and ingestion-based exposures to environmental contaminants that are present in foods, air, and water. As a means of dealing with this problem, a new methodology for estimating breathing rates is presented that is based on the oxygen uptake associated with energy expenditures and a ventilatory equivalent that relates minute volume to oxygen uptake. Three alternative energy-based approaches for estimating daily inhalation rates are examined: (1) average daily intakes of food energy from dietary surveys, adjusted for under reporting of foods; (2) average daily energy expenditure calculated from ratios of total daily expenditure to basal metabolism; and (3) daily energy expenditures determined from a time-activity survey. Under the first two approaches, inhalation rates for adult females in different age cohorts ranged from 9.7 to 11 m^3 d^{-1}, whereas for adult males the range was 13 to 17 m^3 d^{-1}. Inhalation rates for adults determined from activity patterns were higher (i.e., 13 to 18 m^3 d^{-1}), however, those rates were shown to be quite sensitive to the energy expenditures used to represent light and sedentary activities. In contrast to the above estimates, the ICRP 23 reference values for adult females and males are 21 and 23 m^3 d^{-1} (Snyder et al. 1975). Finally, the paper provides a technique for determining the short-term breathing rates of individuals based on their basal metabolic rate and level of physical activity.**
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INTRODUCTION

A KEY INPUT to assessments of the health risks of inhalation exposures to gaseous and particulate contaminants in air is the rate at which exposed individuals breathe air during the period of interest. The inhalation rate controls the transport of airborne contaminants to the respiratory tract and also influences their deposition onto surfaces of the conducting airways and the pulmonary region. For some radionuclides internal doses to organs are due almost solely to inhalation exposures (e.g., plutonium), and, therefore, it is important to have accurate estimates of the breathing rates for the population cohort(s) of concern. Under or over estimation of the breathing rates will produce undesirable biases in estimates of dose and health risk. For example, erroneously high inhalation rates will result in underpredictions of the toxic potential of an airborne contaminant because the higher the dose of a substance per unit toxic response, the less potent it becomes. The reverse is true for low estimates of respiration rates. Although there have been many respiratory measurements of individuals performing various tasks, no studies have systematically measured the inhalation rates that are associated with the diurnal activities of different population cohorts.

On the surface this deficiency may seem odd because breathing rates are such a fundamental physiologic parameter. However, to directly measure these rates among free-living individuals would require that they wear personal breathing-rate monitors that meter air flows. Except for specific activities carried out over relatively short periods of time, this measurement method would be prohibitively cumbersome and awkward. Moreover, subjects are likely to alter their breathing patterns during the monitoring period, producing respiration rates that are not necessarily representative of normal conditions.

Breathing rates recommended for use in dose assessments today are based primarily on short-term measurements of ventilation rates for nonrandom samples of adults who are at rest or who are performing selected tasks of varying physical intensity (Snyder et al. 1975; U.S. EPA 1989). An average daily breathing rate is estimated as a time-weighted-average value of the ventilation rates for rest periods and the ventilation rates required to support the physical activities indicative of the population of interest. One drawback to this method of estimation is that the derived inhalation rates are not necessarily consistent with the breathing rates required for the metabolic conversion of the food nutrients in the diets of the exposed population. Failure to characterize the dependent relationship between breathing and food ingestion in dose assessments can

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distort the relative importance of these two routes of exposure (see Zach and Barnard 1987).

The goal of this paper is to present a method for determining metabolically consistent inhalation rates for use in quantitative dose assessments of airborne radionuclides. Specifically, breathing rates are derived for various age and sex cohorts that are based on energy expenditures of the respective cohorts. The paper begins with a background discussion of some of the guiding principles for deriving inhalation rates as well as a review of inhalation rates that have been proposed by others. Next, the basic methodology used to estimate inhalation rates is presented, followed by a systematic examination of each of the relevant input parameters, including metabolic requirements of individuals, and the relationship between oxygen uptake and breathing rate. The use of food-energy intakes, as recorded in dietary surveys, to estimate energy expenditures is also evaluated. In the final section of the paper, inhalation rates are derived for use in assessments of both short and long-term exposures to atmospheric contaminants.

BACKGROUND

Our breathing is controlled primarily by the amounts of oxygen consumed in the metabolic conversion of food nutrients (i.e., protein, fat, and carbohydrates) to energy. The demand for oxygen and nutrient intakes, as depicted in Fig. 1, is a function of our energy expenditures. Important factors influencing both nutrient and oxygen consumption, and hence breathing rates, are age, gender, weight, health status, and activity patterns (i.e., frequencies and durations of various physical activities). Consequently, breathing rates used in dose assessments should reflect the physiologic, demographic, and lifestyle characteristics of the population at risk.

Another consideration in the derivation and use of inhalation rates is the duration of the exposure, as health-risk assessments of airborne radioactive and nonradioactive substances deal with potential health

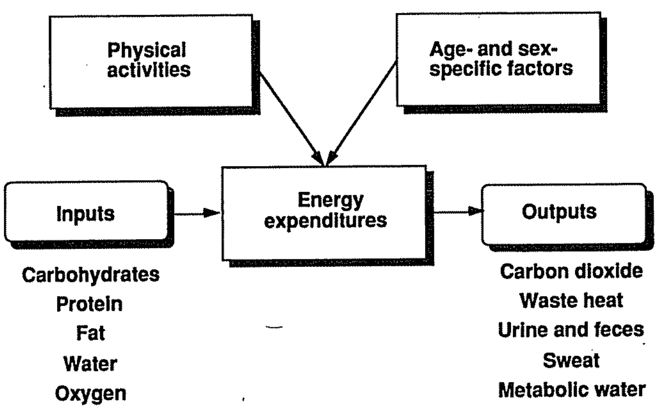

Fig. 1. Conceptual framework that defines the principal factors affecting oxygen and nutrient intakes and waste products.

effects resulting from both short-term (i.e., acute) and long-term (i.e., chronic) exposures. In this regard, short-term inhalation rates should be related directly to the physiologic attributes of an individual and the nature of the physical activities expected during an exposure period. Estimates of chronic exposure to radionuclides present in both food and air should be based on breathing rates that are coupled to the food-energy intakes of diets, which are direct measures of energy expenditures (and associated oxygen requirements) so long as an individual is not changing weight significantly over the time frame of interest.

A standard measure of respiration is termed the minute volume, which is simply the volume of air that is exhaled in a minute. This volume (denoted here as $\dot{V}_E$) is equal to the product of the number of respiratory cycles in a minute (f) and the volume of air respired in each breath (termed the tidal volume, or V_T). At rest, typical adults breathe about 11 to 18 times per minute and have tidal volumes of about 0.4 to 0.7 L (Orzalesi et al. 1965; Gilbert et al. 1972). Minute volumes for adults at rest range between 5 and 8 L min^{-1}. In addition to age and gender-related differences in respiratory parameters, Roy et al. (1991) have shown that V_T and f vary between some ethnic groups. The respiratory system consists of two major components: airways that transport air into the lungs and return exhaled respiratory gases (e.g., CO_2) and the alveoli where gas exchange takes place with pulmonary blood. The conducting airways consist of the nasopharyngeal region (the nasal and oral passages leading to the pharynx) and the tracheobronchial region, which begins with the trachea that leads to two bronchi that channel air to each lung. Those bronchi in turn branch into successively smaller airways that ultimately connect to the alveoli. The conducting airways condition the inhaled air by warming it to body temperature and saturating it with water vapor. Therefore, volumes of inhaled and exhaled air will be slightly different. The minute volume, as noted earlier, is based on exhaled air and is given at body temperature, ambient pressure, with air saturated with water vapor (BTPS).

The historic approach for estimating the breathing rate over a specified period of time is to calculate a time-weighted-average of ventilation rates associated with physical activities of varying durations (referred to here as the time-activity-ventilation approach or simply TAV). In mathematical form the TAV can be expressed as

$$\dot{V}_E = \frac{1}{T} \sum_{i=1}^{k} \dot{V}_{E,i} t_i, \qquad (1)$$

where $\dot{V}_E$ is the time-weighted-average minute volume (L min^{-1}), t_i is the duration if the ith activity (min), $\dot{V}_{E,i}$ is the corresponding minute volume, k is the number of activity periods, and T is the total min of the exposure period (e.g., a day). The authors of ICRP Publication 23 (Snyder et al. 1975) used this activity-based approach to derive daily breathing rates for reference adult males and females as well as children (10 y), infants (1 y), and newborns. A representative day was assumed to consist of 480 min of rest and 960 min of light activity, divided evenly between occupational and nonoccupational activities. The minute volumes at rest for the reference adults were 7.5 and 6 L min^{-1} for males and females, respectively, while active minute volumes were 20 and 19 L min^{-1}. The resulting daily ventilation rates for the two genders are 23 and 21 m^3 d^{-1}. These values have subsequently been used in many assessments of exposures to airborne contaminants. More recently, Roy and Courtay (1991) used a similar, but more refined, TAV approach to estimate inhalation rates for children and adults. Their respective estimated inhalation rates for men and women living sedentary lifestyles are 23 and 18 m^3 d^{-1}.

Time-activity studies indicate that 8 h is a reasonable estimate of the time adults spend asleep or resting (Hill 1985; Szalai 1972), but there are only limited data on the frequencies and durations which various gender/age cohorts spend at specific physical activities (traditional time-activity budgets cover categories or types of activities that are not characterized in terms of energy expenditures). And even if such information were available, literature data on minute volumes may be inapplicable because of the use of an inappropriate cohort and/or activities that are not consistent with the activities engaged in by the target population in a dose assessment. There is already some evidence indicating that the daily breathing volumes calculated using the TAV approach overestimate actual respiration. Irlweck et al. (1980), for example, showed that the measured burdens of $^{239,\,240}$Pu in the lungs of deceased Austrians could not be predicted using an inhalation rate of 22 m^3 d^{-1}. Instead, they found that an inhalation rate of 15 m^3 d^{-1} provided a much better agreement between the measured and predicted $^{239,\,240}$Pu burdens in lungs.

There are few respiratory measurements on children, and hence researchers have developed alternative techniques for estimating inhalation rates for infants, children, and teenagers. James (1988), for example, calculated the inhalation rate of a child at age t as the product of the inhalation rate of an adult and a ratio (R) of the child's energy expenditure to that of an adult. The formula for the time-dependent value of $R(t)$ (Adams 1981) is

$$R(t) = (M(t)/70)\exp[0.047\ (21 - t)] \qquad (2)$$

where

$M(t)$ = body weight of the child, kg; and
t = age of child, y, for $t < 21$.

Eqn 2 is based on the observed decrease in metabolism (in kJ kg^{-1} (b.w.) d^{-1}) as an individual increases in age and the assumption that breathing rate is proportional to oxygen uptake, which in turn is related directly to energy expenditure. Thus, the value of $R(t)$ for a 7-y-old child weighing 25 kg is 0.69, and the estimated breathing rate is 0.69 × 22 m^3 d^{-1} (i.e., adult breathing rate) or 15 m^3 d^{-1}. In contrast to this metabolically-based approach, Hofmann et al. (1979) fit empirical equations to changes in V_T and f with age. Inhalation rates were then calculated as the product of the age-specific respiratory parameters, adjusted for different levels of physical activity. Kleinman (1991) calculated resting minute volumes as the products of V_T and f, which in turn were functions of body weight. Breathing rates for different activity states were computed as multiples of the resting ventilation rate.

METHODOLOGY

As an alternative to the activity-based approach for estimating breathing rates, it is proposed that inhalation rates be calculated from the oxygen consumption supporting personal energy expenditures for short (~hours) and long (weeks and months) periods of time. The basic equation for calculating energy-dependent inhalation rates is

$$\dot{V}_E = E \times H \times VQ, \qquad (3)$$

where

E = energy expenditure rate, kJ d^{-1};
H = volume of oxygen (at standard temperature and pressure, dry air; or STPD) consumed in the production of 1 kJ of energy expended, L kJ^{-1}; and
VQ = the ventilatory equivalent, ratio of the minute volume ($\dot{V}_E$, in L min^{-1} at BTPS) to the oxygen uptake rate ($\dot{V}_{O_2}$ in L min^{-1} at STPD), unitless.

For short exposures to airborne gases or particulates, ventilation rates will be calculated as a function of energy expenditures that are multiples of the basal metabolic rates of defined age/gender cohorts. Ventilation rates representative of longer periods of time (i.e., weeks and months) can be derived from dietary studies that include data on food-energy intakes or energy expenditures expressed as a multiple of an individual's basal metabolic rate (BMR). The BMR is the minimum amount of energy required to support basic cellular respiration while at rest and not actively digesting food. In the following sections, data on each of these parameters are examined.

Oxygen Uptake Factor, H

The metabolism of fat, protein, and carbohydrates results in the consumption of oxygen, the formation of carbon dioxide and water, and the production of energy necessary to sustain our basal metabolic requirement as well as the energy requirements associated with tissue synthesis, physical activities, and thermogenesis (energy associated with the metabolism of food and storage of ingested food nutrients; James et al. 1989). Oxidation of a gram of carbohydrate consumes 0.83 L of oxygen, while each L of oxygen yields 21 kJ (5.0 kcal) of energy. Fat metabolism requires 2 L O_2 g^{-1} and produces 19.7 kJ L^{-1} O_2 (4.7 kcal L^{-1} O_2), while protein metabolism consumes 0.97 L O_2 g^{-1} and generates 18.9 kJ L^{-1} O_2 (4.5 kcal $L^{-1}O_2$) (McLean and Tobin 1987). The oxygen uptake factor, H, is simply the reciprocal of the energy yield of oxygen consumption, and equals 0.0476, 0.0508, and 0.0529 L O_2 kJ^{-1} (0.20, 0.21, and 0.22 L O_2 $kcal^{-1}$) for carbohydrates, fat, and protein. Normal diets contain a mix of these three basic components of food, and to develop a representative value of H, the contributions of each of these food components to the total energy content of typical diets must be quantified. The 1977–1978 Nationwide Food Consumption Survey (NFCS) (USDA 1984), a major study of food intakes among 30,770 individuals from 14,035 randomly sampled households in the U.S., revealed that fat in the average diet comprised 41% of the daily caloric intake, protein 16%, and carbohydrates 42%. Results of another large dietary study (20,322 participants from the U.S.) known as the second National Health and Nutrition Examination Survey (NHANES II) (U.S. DHHS 1983) gave a comparable breakdown, with the same nutrients contributing 38%, 16%, and 46% of the daily energy intakes. The weighted-average oxygen uptake factor for both surveys is 0.05 L O_2 kJ^{-1} (0.21 L O_2 $kcal^{-1}$), which is equivalent to 20 kJ L^{-1} O_2 (4.8 kcal L^{-1} O_2).

Ventilatory Equivalent, VQ

The ventilatory equivalent (VQ) is defined as the ratio of minute volume to oxygen uptake. The value of this ratio varies from individual to individual, reflecting variations in oxygen uptake efficiency, lung physiology, metabolic efficiency, etc. Typical values of VQ reported in the literature range from about 25 to 30 for adults who are at rest or are performing light to moderate physical activity. Grodins (1950), in a summary of early work on measurements of ventilation and oxygen consumption, showed that there is a linear relationship between $\dot{V}_E$ and $\dot{V}_{O_2}$ up to an oxygen uptake rate of approximately 2.5 L/min. The slope of the linear portion of the $\dot{V}_E/\dot{V}_{O_2}$ curve presented by Grodins was about 25 (based on 611 separate respiratory measurements on 86 subjects). In another study, McArdle et al. (1976) measured the $\dot{V}_E$ and $\dot{V}_{O_2}$ values for six male subjects exercising in air and water at different temperatures and exercise levels. Below an oxygen uptake of 2.5 L min^{-1} the ratio $\dot{V}_E$ to $\dot{V}_{O_2}$ was 25 and above this, VQ equaled about 30. Measurements of $\dot{V}_E$ and $\dot{V}_{O_2}$ in other studies involving respiratory responses to exercise have given similar results (e.g., Cunningham 1963; Wasserman et al. 1967). As a means of evaluating independently the earlier work, additional respiratory measurements of $\dot{V}_E$ and $\dot{V}_{O_2}$ reported in the open literature were located, and the resulting data set† contained 159 respiratory measurements on 75 adults studied by five separate sets of researchers (Bachofen et al. 1973; Grimby et al. 1966; Lambersten et al. 1959; Saltin and Astrand 1967; Salzano et al. 1984). Most of the subjects studied by the researchers were male, and many of the subjects were athletes. As shown in Fig. 2, there is a linear relationship between $\dot{A}_E$ and $\dot{V}_{O_2}$ over a wide range of oxygen-uptake rates associated with resting (i.e., $\dot{V}_{O_2} < 0.3$ L min^{-1}) conditions as well as with elevated physical activity such as running (i.e., $\dot{V}_{O_2} > 2$ L min^{-1}). The regression equation for data points is $\dot{V}_E = 27\ \dot{V}_{O_2}^{0.99}$ ($r^2 = 0.96$). The gap in the respiratory measurements in Fig. 2 for $\dot{V}_{O_2}$ values between 0.4 and 0.9 L O_2 min^{-1} is due to the experimental protocols adopted by some of the researchers. Often measurements were made while subjects were at rest and then at elevated levels of physical activity that had breathing requirements which were considerably above those at rest. The geometric mean (GM) of the VQ values is 27 with a geometric standard deviation (GSD) of 1.18 (see Fig. 3 for a logprobability plot of the data). The VQ value calculated here is higher than the value of approximately 25 found in earlier studies, however, it is important to note that the updated data set spans a larger range of respiratory rates. In addition, the geometric mean value of VQ is an intermediate value between the low and high VQ values (i.e., 25 and 30) reported for different levels of $\dot{V}_{O_2}$. Respiratory measurements of newborns give similar estimates of VQ. For example, the geometric mean value of the VQ values for 44 newborns studied by Stahlman and Meece (1957) was 28.1, with a GSD of 1.3. In contrast, the GM value of the $\dot{V}_E/\dot{V}_{O_2}$ measurements of 17 newborns by Cook et al. (1955) was 24.6 with a GSD of 1.23.

In summary, the analyses of $\dot{V}_E$ and $\dot{V}_{O_2}$ have demonstrated that there is a strong linear relationship between these two variables and that most of the values of VQ derived from the literature fall within the 68% confidence interval (i.e., 23 to 32) of the lognormal distribution for VQ. The existing data base, though, can be improved by making additional respiratory measurements using (1) randomly-selected individuals from the U.S. population to evaluate the significance

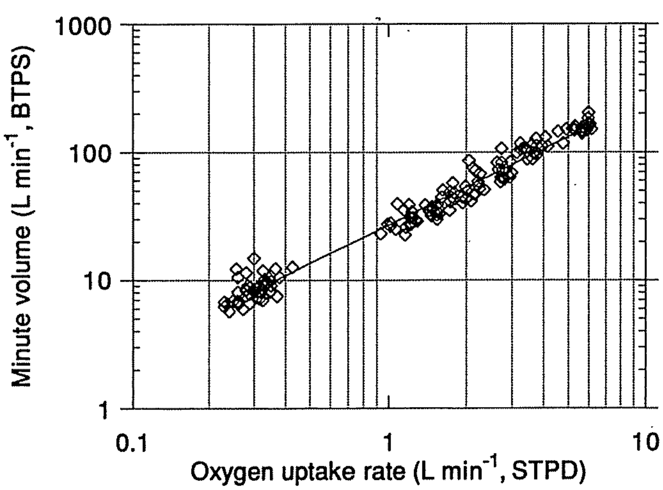

Fig. 2. Plot of 159 measurements of minute volumes and related oxygen uptake rates for 75 subjects.

† Available upon request from the author.

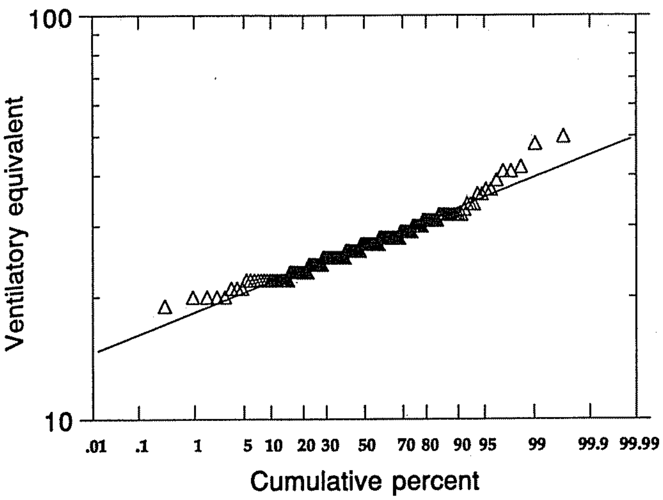

Fig. 3. Logprobability plot of the 159 ventilatory equivalents (VQ) calculated from the $\dot{V}_E$ and $\dot{V}_{O_2}$ data for 75 subjects. The geometric mean of the VQ values is 27 with a geometric standard deviation of 1.18.

of age and gender-related differences in VQ and (2) individuals with abnormal lung function to determine how their ventilatory equivalents differ from those of the general population.

Energy Expenditures, E

Our energy expenditures and related oxygen uptake and ventilation rates are constantly changing as we go about our daily routines. Selection of an appropriate inhalation rate to characterize respiration depends entirely on the objectives of the dose assessment. In order to use eqn (3) to estimate the ventilation rates, the equivalent energy expenditures must be determined for the exposure periods of interest. Energy expenditures for short-term activities can be estimated by multiplying an individual's basal metabolic rate by a factor that is indicative of a particular activity (commonly referred to as a metabolic equivalent or MET). The value of this approach is that the calculated energy expenditure rate reflects both the intensity of the activity as well as the physiologic attributes of the individual that govern the BMR. For longer periods of time, energy expenditures can be approximated by food-energy intakes. Energy expenditures under various conditions are discussed below.

Energy expenditures for rest and activities. The metabolic rate of an individual who is lying down or resting is termed the resting metabolic rate (RMR). This measure of metabolism includes the energy required for food digestion, and it is only about 10% higher than the BMR. Consequently, the two parameters are often used interchangeably (Guthrie 1983). However, because there is no operational definition of the "resting" state, the RMR could actually exceed the BMR by much greater amounts. An individual's resting metabolism is affected by such factors as age, gender, weight, and lean-body mass. Schofield (1985) analyzed statistically metabolic data for thousands of individuals and developed regression equations to predict the BMR of males and females from their age and body weight. Information on the cohorts and the related regression equations are shown in Table 1.

As a means of categorizing different energy expenditures as a function of an individual's BMR, the MET values for different physical activities are summarized in Table 2. As expected, the lowest multipliers are for sedentary activities such as sitting at a desk or watching television. A variety of household activities require energy expenditures that are between 2 and 4 times an individual's BMR. At more moderate levels of activity (for example, recreational activities consisting of volley ball, table tennis, cycling, and swimming), the multipliers range from 3 to 5. On the basis of these data, the following categories of activities and corresponding BMR multipliers are proposed for estimating energy expenditures for physical activities of varying intensity:

- sedentary: 1.2 × BMR
- light: 1.5 to 2.0 × BMR
- moderate: 3 to 5 × BMR
- heavy: 10 to 20 × BMR

Thus, an adult male with a BMR of 290 kJ h^{-1} (70 kcal h^{-1}) would expend between 870 and 1450 kJ h^{-1} (210 and 350 kcal h^{-1}) engaged in physical activities of moderate intensity such as floor sweeping, vacuuming, and recreational swimming.

Food-energy intakes. Under steady-state conditions in which an individual is neither gaining or losing body weight, energy expenditures associated with our basic metabolic requirements and with our physical activities must equal food-energy intakes. Therefore, the energy content of a person's diet can be used to estimate his or her energy expenditures and related respiratory requirements over periods of weeks and months. Table 3 contains the average food-energy intakes reported for individuals in different age/gender cohorts sampled in the 1977–1978 NFCS. The NFCS surveyed the food intakes of individuals (randomly sampled from the U.S. population) for three consecutive days, two days of which were derived from a diary and one day from a 24-h recall to an interviewer. The nutritional adequacy of the recorded dietary intakes can be evaluated by comparing the food-energy intakes to BMR values for each of the cohorts, estimated from the appropriate BMR equations given in Table 1. The ratios of daily energy intake (denoted EFD) to the BMRs ranged from 1.9 for growing infants to 1.1 for females 23 to 65 years old. For adult males (i.e., >18 y) the EFD/BMR ratios averaged about 1.3. In the NHANES II study (this dietary survey only recorded food intakes for one day) adult males had slightly higher food-energy intakes relative to their predicted BMR requirements (i.e., 1.4), but the women

Table 1. Statistics of the age/gender cohorts used to develop regression equations for predicting basal metabolic rates (from Schofield 1985)

Gender/age (y)	BMR MJ d^{-1}	±SD	CV[a]	Body wt. kg	n	BMR equation[b]	r
Males							
Under 3	1.51	0.918	0.61	6.6	162	0.249 bw − 0.127	0.95
3 to < 10	4.14	0.498	0.12	21	338	0.095 bw + 2.110	0.83
10 to < 18	5.86	1.171	0.20	42	734	0.074 bw + 2.754	0.93
18 to < 30	6.87	0.843	0.12	63	2879	0.063 bw + 2.896	0.65
30 to < 60	6.75	0.872	0.13	64	646	0.048 bw + 3.653	0.6
60 +	5.59	0.928	0.17	62	50	0.049 bw + 2.459	0.71
Females							
Under 3	1.54	0.915	0.59	6.9	137	0.244 bw − 0.130	0.96
3 to < 10	3.85	0.493	0.13	21	413	0.085 bw + 2.033	0.81
10 to < 18	5.04	0.780	0.15	38	575	0.056 bw + 2.898	0.8
18 to < 30	5.33	0.721	0.14	53	829	0.062 bw + 2.036	0.73
30 to < 60	5.62	0.630	0.11	61	372	0.034 bw + 3.538	0.68
60 +	4.85	0.605	0.12	56	38	0.038 bw + 2.755	0.68

[a] Coefficient of variation (SD/mean).
[b] Body weight (bw) is in kg.

Table 2. BMR multipliers for physical activities of light to heavy intensity (from Durnin and Passmore 1967; Saltin and Astrand 1967)

Activity level	BMR multiplier
Sedentary	1.2
Light	
Knitting/sewing	1.3
Standing	1.5
Floor sweeping	1.8
Preparing vegetables	1.8
Office work	1.8
Moderate	
Carpet sweeping	2.7
Cooking	2.7
Preparing a meal	2.7
Dish washing	2.7
Volley ball	3.0
Table tennis	3.0
Light industry	3.1
Walking	3.5
Bed making	3.8
Vacuuming	3.8
Cycling	5.3
Swimming	5.3
Dancing	5.3
Heavy	
Various sports events	10 to 22
Heavy industrial work	10

older than 45 y had energy intakes that were essentially equal to their estimated BMRs! A more recent study that focused specifically on adult women in the U.S. was the Continuing Survey of Food Intakes by Individuals (CSFII) (USDA 1987). This survey sampled 1088 women in the 19 to 50 y age bracket. Food intakes were determined for four nonconsecutive days. The average energy intake for women aged 19 to 34 y was 6.66 MJ d^{-1} (1590 kcal d^{-1}), decreasing to 6.11 MJ d^{-1} (1458 kcal d^{-1}) for women aged 35 to 50 y. Average body weights for the two age groups were 62 and 66 kg, and their estimated BMRs were 5.95 and 5.78 MJ d^{-1} (1420 and 1380 kcal d^{-1}). The associated EFD/BMR ratios are 1.1 and 1.06.

The low ratios of food-energy intakes to estimated basal metabolic rates of the women sampled in the above surveys indicates that there is a consistent bias or under-reporting of the foods consumed. Similar bias probably occurs for the males surveyed as well. Part of the bias may be due to the methods used to ascertain dietary intakes as well as the shortness of surveys, which may not truly capture regular food-intakes over extended periods (NRC 1986). Acheson et al. (1980) conducted a study in which 12 individuals at an Antarctic research station recorded and weighed all foods eaten over several weeks and once a week filled out a dietary questionnaire to record (recall) the food consumed during the previous 24 h. The caloric content of the meals was derived by multiplying food weights (estimated from recall or measured) by their caloric content obtained from food-composition tables. The geometric-mean ratio of the caloric intakes of weighed foods to the caloric contents of reported foods (24-h recall) was 1.24 (GSD = 1.13). In a study of obese males, Sopko et al. (1984) found that the caloric intakes based on the dietary records of individuals in four weight groups were consistently lower than the intakes derived from indirect measurements of the foods consumed (GM ratio of measured/recorded intakes for the four groups was 1.18).

Total energy expenditures. The relationships between energy intakes, expenditures, and BMR can be evaluated further by comparing EFD/BMR ratios for men and women participating in other dietary studies. For example, in a year-long dietary study conducted by Basiotis et al. (1989), the average EFD/BMR ratio for the 16 female participants (aged 20 to 53 y) was 1.38 (±0.24), whereas the mean EFD/BMR ratio for the 13

Table 3. Comparisons of estimated basal metabolic rates with average food-energy intakes for individuals sampled in the 1977–1978 NFCS (USDA 1984)

Cohort/age (y)	Body wt. kg	BMR[a] MJ d^{-1}	BMR[a] kcal d^{-1}	Energy intake (EFD) MJ d^{-1}	Energy intake (EFD) kcal d^{-1}	Ratio EFD/BMR
Children						
Under 1	7.6	1.74	416	3.32	793	1.90
1 to 2	13	3.08	734	5.07	1209	1.65
3 to 5	18	3.69	881	6.14	1466	1.66
6 to 8	26	4.41	1053	7.43	1774	1.68
Males						
9 to 11	36	5.42	1293	8.55	2040	1.58
12 to 14	50	6.45	1540	9.54	2276	1.48
15 to 18	66	7.64	1823	10.8	2568	1.41
19 to 22	74	7.56	1804	10.0	2395	1.33
23 to 34	79	7.87	1879	10.1	2418	1.29
35 to 50	82	7.59	1811	9.51	2270	1.25
51 to 64	80	7.49	1788	9.04	2158	1.21
65 to 74	76	6.18	1476	8.02	1913	1.30
75 +	71	5.94	1417	7.82	1866	1.32
Females						
9 to 11	36	4.91	1173	7.75	1849	1.58
12 to 14	49	5.64	1347	7.72	1842	1.37
15 to 18	56	6.03	1440	7.32	1748	1.21
19 to 22	59	5.69	1359	6.71	1601	1.18
23 to 34	62	5.88	1403	6.72	1603	1.14
35 to 50	66	5.78	1380	6.34	1514	1.10
51 to 64	67	5.82	1388	6.40	1528	1.10
65 to 74	66	5.26	1256	5.99	1430	1.14
75 +	62	5.11	1220	5.94	1417	1.16

[a] Calculated from the appropriate age and gender-based BMR equations given in Table 1.

men (aged 22 to 49 y) was 1.59 (±0.33). James et al. (1989) summarized the results of five studies that examined the food-energy intakes of people over 60 y old. The average ratios of food-energy intakes to estimated basal metabolic rates for women in three studies reviewed were 1.25, 1.49, and 1.57, while for men the averages were 1.5 (average of two samples reported in one study), 1.38, 1.62, and 1.58. Griffiths and Payne (1976) reported that the average food-energy intake for a group of 12 children aged 4 to 5 y was 6.00 MJ d^{-1} (1433 kcal d^{-1}). The average BMR of the group (based on an average body weight of 19 kg) is 3.78 MJ d^{-1}, and therefore the estimated EFD/BMR is 1.58.

Additional information on the relationship between energy expenditure and basal metabolism comes from metabolic studies conducted using doubly-labeled water. In this experimental approach, doubly-labeled water (i.e., $^2H_2{}^{18}O$) is administered to an individual and the differences in the turnover rates of the oxygen and hydrogen isotopes in body water (assayed in urine) are used to estimate carbon dioxide production and energy expenditure (see Schoeller and van Santen 1982). Prentice et al. (1985) used this technique to measure the metabolism of 12 women aged 23 to 40 y over periods of 14 to 21 d. The average ratio of total metabolism to resting metabolism was 1.38 (±0.16), with a range of 1.2 to 1.8. This result is comparable to the value of 1.36 that was calculated for the females in the dietary study conducted by Basiotis et al. (1989). In a study of six males aged 20 to 32 y who were engaged in light agricultural activities, Riumallo et al. (1989) found that the doubly-labeled water approach gave estimates of energy expenditure that were in good agreement with food-energy intakes. The average ratio of energy expenditure to BMR (estimated from the body weights given) for the group was 1.78 (±0.12). Roberts et al. (1988) used the doubly-labeled water technique to measure the energy expenditures of infants aged 3 mo who were born to lean, normal, and overweight mothers. The ratio of daily energy expenditure (excluding food energy deposited as tissue) to BMR is calculated to be 1.4 for six infants (weighing an average of 5.77 kg) born to mothers of normal weight.

Energy expenditures for active and inactive hours. The ratio of EFD/BMR has been used routinely to evaluate the adequacy of food-energy intakes, however, one limitation of this ratio is that it provides limited information on the intensity of physical activity during active hours. The magnitude of the EFD/BMR ratio based on energy expenditures for active and inactive hours can be estimated from the following expression:

$$A = [(24 - S)F + S]/24, \qquad (4)$$

where A is equal to EFD/BMR, S is the number of hours spent sleeping each day, and F is the ratio of the rate of energy expenditure during active hours to the estimated BMR. The value of F can be computed as

$$F = (24A - S)/(24 - S). \qquad (5)$$

A person who leads a sedentary lifestyle during 16 waking hours with $F = 1.25$ (and $S = 8$ h) is calculated to have an EFD/BMR ratio of 1.17. If F increases to 1.5, the ratio becomes 1.33. With A equal to 1.35 for women and $S = 8$, the value of F is 1.52, which is indicative of sedentary and light physical activities during active hours. With A equal to 1.55 for men, F equals 1.82, which reflects light physical activities. These values are not unreasonable given differences in the occupational status of men and women (percents employed of each gender), the kinds of labor-intensive jobs representative of men and women, leisure hours dominated by television viewing, and the increasingly sedentary lifestyles that are characteristic of service-oriented economies (Molitor 1990).

INHALATION RATES FOR VARIOUS AGE AND GENDER COHORTS

The energy expenditures for specific physical activities and for the collective activities that describe our normal lifestyles represent the basic inputs to the methodology for determining ventilation rates of the lungs. Key determinants of these energy expenditures are the age and gender of the individuals that inhale air contaminants released to indoor/outdoor air from continuous (chronic) or transient sources. The subsections below present estimates of inhalation rates for short and long-term inhalation exposures.

Inhalation Rates for Short Term Inhalation Exposures

The quantification of an appropriate inhalation rate for a short-term exposure to an airborne contaminant is problematic because there is obviously a continuum of physical activities that characterize the behavior of an individual or population group over periods lasting just minutes or hours. To facilitate analyses of the inhalation rates associated with various combinations of physical activities, Table 4 provides estimates of $\dot{V}_E$ for six age/gender cohorts and four energy-expenditure categories (defined by the sets of MET values discussed earlier). The inhalation rates calculated for adults at rest (i.e., 7.0 to 7.2 and 5.4 to 5.5 L min^{-1} for males and females, respectively) are comparable to the values presented in Roy and Courtay (1991) (i.e., 7.5 and 5.4 L min^{-1}). It should be pointed out, however, that inhalation estimates based on basal metabolic rates will generally be lower than inhalation rates determined while individuals are at rest during waking hours. For example, the mean ventilation rate of six females between 18 to 30 years of age and weighing an average of 52 kg in a study by Gilbert et al. (1972) was 6.5 L min^{-1}, derived from measurements made after one hour of quiet breathing in bed. In contrast, our BMR-based estimate for the breathing rate of these individuals, which does not include thermogenesis, is 4.9 L min^{-1}, or 25% lower.

The inhalation rates calculated for differing levels of physical activity (see Table 4) are similar to the minute volumes presented in a summary of inhalation rates presented by the U.S. EPA (1989). In the U.S. EPA analysis, which grouped minute volumes according to the results of a literature survey of measured values, the average minute volumes for light, moderate, and heavy activities for adult males were 14, 41, and 80 L min^{-1}, and for adult females the values were 8, 26, and 48 L min^{-1}. For comparison, our values for the same categories are 15, 30, and 74 L min^{-1} for adult males and 12, 24, and 59 L min^{-1} for females. The MET values defined for each activity category (see Table 4) can be used to define lower and upper limits of the associated inhalation rates. If more refined estimates of short term inhalation rates are required, the BMR of a specific individual can be calculated from the applicable equation in Table 1 and adjusted according to the METs for the various activity categories. Eqn 3 can then be used to compute the ventilation rate.

Inhalation Rates for Chronic Inhalation Exposures

Under steady-state conditions, food-energy intakes equal energy expenditures and the inhalation rate is a direct function of the associated uptake of oxygen to metabolize dietary fats, carbohydrates, and protein. But as discussed earlier, large dietary surveys of the U.S. population, such as the NFCS, apparently underestimate food-energy intakes due to biases that are introduced as individuals record or recall the quantities of foods and beverages consumed. Three alternative approaches are therefore proposed for estimating chronic inhalation rates for different age/gender cohorts of the U.S. population: (1) breathing rates based on NFCS food-energy intakes that are adjusted upward to compensate for reporting biases; (2) breathing rates determined from energy expenditures that are multiples of the average BMR of various age/gender cohorts; and (3) breathing rates computed for energy expenditures estimated for the times spent at different levels of physical activity.

Table 5 presents estimates of the inhalation rates for each of the age/gender cohorts addressed in the 1977–78 NFCS. These estimates were obtained by multiplying all of the energy intakes for individuals age 9 y and older in Table 3 by a constant factor of 1.2 to compensate for the apparent bias in the NFCS. This factor is the average of the two bias factors determined from the studies of Acheson et al. (1980) and Sopko et al. (1984). Food-energy intakes for children under 9 y were not adjusted because they are comparable to intakes determined in other studies (e.g., Wait et al. 1969; Griffiths and Payne 1976; Magarey and Boulton 1987). Fig. 4 shows how the inhalation rates vary with age and gender. Daily inhalation peaks at age 15 to 18 y (17 m^3 d^{-1}) for males, and for females the peak is at 9 to 11 y (13 m^3 d^{-1}). Lifetime-average inhalation rates in Table 5 (i.e., 14 m^3 d^{-1} for men and 10 m^3 d^{-1} for women) were determined as a time-weighted-average value, using the number of years (L) represented by each age cohort. Fig. 5 shows the daily inhalation rates expressed

Table 4. Short-term (i.e., minutes to hours) ventilation rates estimated for six age groups, subdivided by gender. Inhalation rates are calculated from energy expenditure rates for five activity categories ranging from rest to heavy work or exercise

			Activity type				
			Rest	Sedentary	Light	Moderate	Heavy
			MET (BMR multiplier)				
Gender and Age (y)	Weight kg[e]	BMR[a] MJ d^{-1}	1	1.2	2[b]	4[c]	10[d]
			Inhalation rate[f] (L min^{-1})				
Male							
0.5 to < 3	14	3.40	3.2	3.8	6.4	13	32
3 to < 10	23	4.30	4.0	4.8	8.1	16	40
10 to < 18	53	6.70	6.3	7.5	13	25	63
18 to < 30	76	7.70	7.2	8.7	14	29	72
30 to < 60	80	7.50	7.0	8.4	14	28	70
60 +	75	6.10	5.7	6.9	11	23	57
Female							
0.5 to < 3	11	2.60	2.4	2.9	4.9	10	24
3 to < 10	23	4.00	3.8	4.5	7.5	15	38
10 to < 18	50	5.70	5.3	6.4	11	21	53
18 to < 30	62	5.90	5.5	6.6	11	22	55
30 to < 60	68	5.80	5.4	6.5	11	22	54
60 +	67	5.30	5.0	6.0	9.9	20	50

[a] The BMRs for the age/gender cohorts are calculated using the respective body weights and the BMR equations given in Table 1.
[b] Range of 1.5 to 2.5.
[c] Range of 3 to 5.
[d] Range of > 5 to 20.
[e] Body weights are based on the average weights for age/gender cohorts of the U.S. population given in Najjar and Rowland (1987).
[f] The inhalation rate is calculated by multiplying the BMR by the product H × VQ × (d 1440 min^{-1}).

on a body-weight basis. Declines in the inhalation rate reflect decreases in metabolism with age as well as changes in lifestyle.

Inhalation rates are also calculated for inactive (i.e., sleep) and active hours (both in L min^{-1}). Breathing rates for inactive hours were determined from the estimated BMR given in Table 3, while the breathing rate for active hours was computed simply by multiplying the inactive rate by the parameter F (from eqn 5). The hours of sleep for youth under 18 y are estimated from this relationship: $S = 11.2 - 0.18$ age (y) $(R^2 = 0.92)$, which is a linear regression between sleep time (hours) and age (years) for children participating in a time-activity survey summarized by Timmer et al. (1985).

In the second method for determining inhalation rates, an average daily energy expenditure rate for an age/gender cohort is calculated by multiplying the BMR of the population cohort by the parameter A, which is the ratio of total daily energy expenditure to daily BMR. The inhalation rate is calculated as $\dot{V}_E =$ (BMR $\times A \times H \times$ VQ)/1000, where $\dot{V}_E$ is in m^3 d^{-1}. The parameters used to calculate the breathing rates are summarized in Table 6. The mean of the male and female EFD/BMR ratios from the year-long dietary study of Basiotis et al. (1989) are used to represent the A values for adult males and females over 18 y. A mean A value of 1.6 was used to represent the relationship between the BMR and energy expenditures for males and females under 10 y. This BMR multiplier yields energy expenditures that are comparable to the energy intakes measured by Magarey and Boulton (1987) and Wait et al. (1969). The averages of the EFD/BMR ratios given in Table 3 (adjusted by the factor 1.2 to account for food-reporting bias) for the 12 to 14 y and 15 to 18 y age brackets were used to calculate the A values for males and females aged 10 to <18 y. The mean inhalation rates predicted for the cohorts are comparable to the values presented in Table 5. Inhalation rates for adult females (>18 y) in Table 6, for example, range between 9.9 and 11 m^3 d^{-1}, and in Table 5 they range between 9.6 and 11 m^3 d^{-1}. The lifetime-average inhalation rates for males and females, based on the age spans of the respective cohorts, are 14 and 10 m^3 d^{-1}.

The third approach for estimating inhalation rates is based on a factorial method in which the estimated energy expenditures associated with the different levels of physical activity engaged in over the course of an "average" day are converted to equivalent inhalation rates according to eqn (3). In contrast, the factorial approach used in ICRP 23 (Snyder et al. 1975) and Roy and Courtay (1991) determines the inhalation rates for different activities as the product of a ventilation rate that is assumed to correspond with the inhalation requirement (not energy) of the activity and the activity's duration. In order to use an energy-based factorial method to calculate inhalation rates, it is very important to have data on the times spent at physical activities that are classified or grouped according to level of energy expenditure. One study that meets this reporting

Table 5. Daily inhalation rates estimated from the food-energy intakes for cohorts sampled in the 1977–1978 NFCS and estimated inhalation rates for active and inactive periods

Cohort/age (y)	L[c]	Daily[a] inhalation $m^3\ d^{-1}$	Sleep h	MET value A	MET value F	Inhalation rates[b] Inactive	Inhalation rates[b] Active $L\ min^{-1}$
Children							
Under 1	1	4.5	11	1.9	2.7	1.6	4.3
1 to 2	2	6.8	11	1.6	2.2	2.9	6.4
3 to 5	3	8.3	10	1.7	2.2	3.5	7.7
6 to 8	3	10	10	1.7	2.2	4.1	9.0
Males							
9 to 11	3	14	9	1.9	2.5	5.1	13
12 to 14	3	15	9	1.8	2.2	6.1	13
15 to 18	4	17	8	1.7	2.1	7.2	15
19 to 22	4	16	8	1.6	1.9	7.1	13
23 to 34	11	16	8	1.5	1.8	7.4	13
35 to 50	16	15	8	1.5	1.8	7.1	12
51 to 64	14	15	8	1.4	1.7	7.0	12
65 to 74	10	13	8	1.6	1.8	5.8	10
75 +	1	13	8	1.6	1.9	5.6	11
Lifetime ave.		14					
Females							
9 to 11	3	13	9	1.9	2.5	4.6	12
12 to 14	3	12	9	1.6	2.0	5.3	11
15 to 18	4	12	8	1.5	1.7	5.7	9.7
19 to 22	4	11	8	1.4	1.6	5.3	8.5
23 to 34	11	11	8	1.4	1.6	5.5	8.8
35 to 50	16	10	8	1.3	1.5	5.4	8.1
51 to 64	14	10	8	1.3	1.5	5.5	8.2
65 to 74	10	9.7	8	1.4	1.5	4.9	7.4
75+	1	9.6	8	1.4	1.6	4.8	7.7
Lifetime ave.		10					

[a] The daily inhalation rate is calculated by multiplying the EFD values in Table 3 by $H \times VQ \times (m^3\ 1000\ L^{-1})$ for those under 9 y and by $1.2 \times H \times VQ \times (m^3\ 1000\ L^{-1})$ for those 9 y and older.
[b] The inhalation rate for inactive periods is calculated as $BMR \times H \times VQ \times (d\ 1440\ min^{-1})$ and for active periods it is computed by multiplying the inactive inhalation rate by F. Values of EFD and BMR are from Table 3.
[c] L is the number of years for each cohort. The lifetime averages were computed by multiplying the individual inhalation rates by the respective L values, summing the products across cohorts, and dividing the result by 75, the total of the cohort age spans.

requirement has been completed by Sallis et al. (1985). In their study, time-activity data were obtained in 1120 women and 1006 men (aged 20 to 74 y) selected randomly from four communities in California. The five physical-activity categories and associated MET values used in the study were sleep, MET = 1; light activity, MET = 1.5; moderate activity, MET = 4; hard activity, MET = 6; and very hard activity, MET = 10. Table 7 presents the durations of the various activities for the eight age/gender cohorts, along with our estimates of the BMRs calculated from body weights in Najjar and Rowland (1987), daily energy expenditures (E), and breathing rates.

Sallis et al. (1985) reported that the average energy expenditures for males and females were 13.3 MJ d^{-1} (±3.74) and 9.57 MJ d^{-1} (±2.21), respectively. The

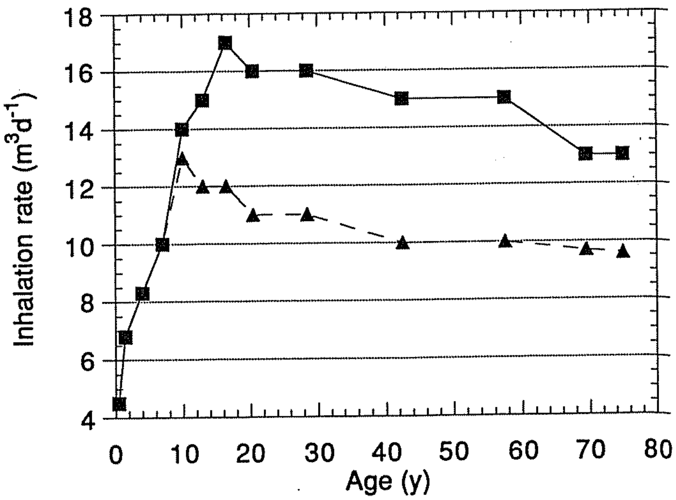

Fig. 4. Inhalation rates for males and females based on food-energy intakes adjusted for reporting bias in the National Food Consumption Survey. Plotted values are for midpoint ages of the age cohorts given in Table 5 (males ■, females ▲).

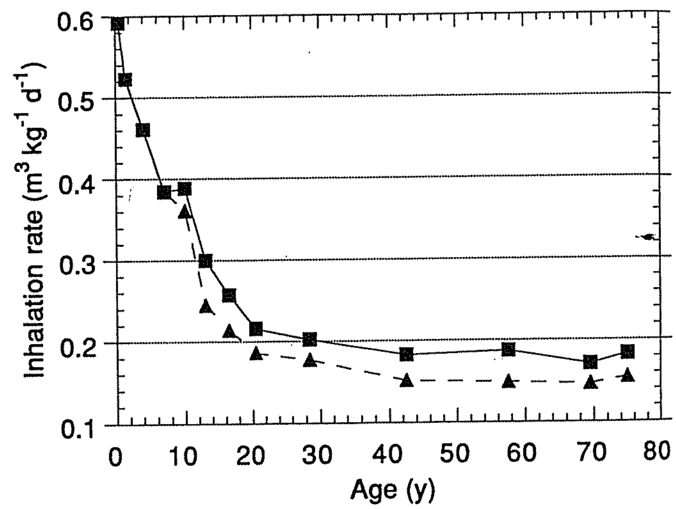

Fig. 5. Inhalation rates for males and females expressed on a body-weight basis. Plotted values are calculated from the daily inhalation rates given in Table 5 and body weights given in Table 3 (males ■, females ▲).

associated inhalation rates are 18 and 13 $m^3\ d^{-1}$ (calculated from eqn 3). They used a constant resting metabolic rate of 4.19 kJ $kg^{-1}\ d^{-1}$ (1 kcal $kg^{-1}\ d^{-1}$) together with the body weights of the respondents to estimate energy expenditures, whereas the estimates used in this paper are based on age and gender-specific BMR values computed from body weights obtained from a random sample of individuals from the U.S. The inhalation rates for females presented in Table 7 are slightly higher than the ones determined using the previous two methods. However, the estimated inhalation rates are particularly sensitive to the MET value chosen to represent the energy expenditures for light

Table 6. Parameter distributions used to estimate inhalation rates as a function of age and gender-specific BMRs and ratios of total energy expenditure to BMR (i.e., the parameter A)

Gender/age (y)	Body weight[a] kg	BMR[b] MJ d^{-1}	VQ[c]	A[d]	H m^3 O_2 MJ^{-1}	$\dot{V}_E$ m^3 d^{-1}
Male						
0.5 to < 3	14	3.4	27	1.6	0.05	7.3
3 to < 10	23	4.3	27	1.6	0.05	9.3
10 to < 18	53	6.7	27	1.7	0.05	15
18 to < 30	76	7.7	27	1.59	0.05	17
30 to < 60	80	7.5	27	1.59	0.05	16
60+	75	6.1	27	1.59	0.05	13
Female						
0.5 to < 3	11	2.6	27	1.6	0.05	5.6
3 to < 10	23	4.0	27	1.6	0.05	8.6
10 to < 18	50	5.7	27	1.5	0.05	12
18 to < 30	62	5.9	27	1.38	0.05	11
30 to < 60	68	5.8	27	1.38	0.05	11
60+	67	5.3	27	1.38	0.05	9.9

[a] Body weights are based on the average weights for age/gender cohorts of the U.S. population given in Najjar and Rowland (1987).
[b] The BMRs for the age/gender cohorts are calculated using the respective body weights and the BMR equations listed in Table 1.
[c] The geometric mean of the ventilatory equivalent is 27. See Fig. 3.
[d] The values of the BMR multiplier for those over 18 y are derived from the Basiotis et al. (1989) study. Multipliers for other age groups were selected so that the predicted energy expenditures are consistent with the results of other studies (see text).

activities, the category with the largest block of time. Sallis et al. (1985) selected an MET of 1.5 to represent light activities "... because most of the activities in this category required very low levels of expenditure." Unfortunately, their survey design only solicited information on the times spent at sleep and moderate, heavy, and very heavy activities. The time spent at light activities was estimated by subtracting the total time of the other four activities from 24 h. No data were obtained on the types and durations of light activities, including sedentary behavior. This approach was taken because the objective of the study was to provide information that could be used to explore the relationship between exercise and health. If the representative MET for light activities is reduced only 5% to reflect nap times and sedentary activities such as television viewing, driving, etc., then the estimated inhalation rates for women aged 50–64 y drops nearly 0.6 m^3 d^{-1} and with a 10% MET reduction, it drops about 0.8 m^3 d^{-1}, and the daily inhalation rate becomes 12 m^3 d^{-1}.

Although each of the three energy-based methods for estimating inhalation rates offer improved estimates of inhalation rates, there are residual uncertainties that need to be addressed. Inhalation estimates based on food-energy intakes, for example, were derived in part from an adjustment made to account for reporting bias in the NFCS. More work is needed to quantify age and

Table 7. Inhalation rates based on the times spent at different physical activities and associated energy expenditures. The hours spent at activities are from Sallis et al. (1985). BMRs are calculated from the metabolic equations in Table 1 and the body weights are from Najjar and Rowland (1987)

Age (y) and Activity	MET	Males					Females				
		weight kg	BMR kJ h^{-1}	Duration h d^{-1}	E MJ d^{-1}	$\dot{V}_E$ m^3d^{-1}	weight kg	BMR kJ h^{-1}	Duration h d^{-1}	E MJ d^{-1}	$\dot{V}_E$ m^3d^{-1}
20–34											
Sleep	1	76	320	7.2	2.3	3.1	62	283	7.2	2.0	2.8
Light	1.5	76	320	14.5	7.0	9.4	62	283	14.5	6.2	8.3
Moderate	4	76	320	1.2	1.5	2.1	62	283	1.2	1.4	1.8
Hard	6	76	320	0.64	1.2	1.7	62	283	0.64	1.1	1.5
Very hard	10	76	320	0.23	0.74	1.0	62	283	0.23	0.65	0.88
Totals				24	13	17			24	11	15
35–49											
Sleep	1.	81	314	7.1	2.2	3.0	67	242	7.1	1.7	2.3
Light	1.5	81	314	14.6	6.9	9.3	67	242	14.6	5.3	7.2
Moderate	4	81	314	1.4	1.8	2.4	67	242	1.4	1.4	1.8
Hard	6	81	314	0.59	1.1	1.5	67	242	0.59	0.9	1.2
Very hard	10	81	314	0.29	0.91	1.2	67	242	0.29	0.70	0.95
Totals				24	13	17			24	9.9	13
50–64											
Sleep	1	80	312	7.3	2.3	3.1	68	244	7.3	1.8	2.4
Light	1.5	80	312	14.9	7.0	9.4	68	244	14.9	5.4	7.4
Moderate	4	80	312	1.1	1.4	1.9	68	244	1.1	1.1	1.4
Hard	6	80	312	0.50	0.94	1.3	68	244	0.5	0.7	1.0
Very hard	10	80	312	0.14	0.44	0.6	68	244	0.14	0.34	0.46
Totals				24	12	16			24	9.4	13
65–74											
Sleep	1	75	256	7.3	1.9	2.5	67	221	7.3	1.6	2.2
Light	1.5	75	256	14.9	5.7	7.7	67	221	14.9	4.9	6.7
Moderate	4	75	256	1.1	1.1	1.5	67	221	1.1	1.0	1.3
Hard	6	75	256	0.5	0.8	1.0	67	221	0.5	0.7	0.9
Very hard	10	75	256	0.14	0.36	0.48	67	221	0.14	0.31	0.42
Totals				24	9.8	13			24	8.5	11

gender-specific biases in such dietary surveys. In addition, the calculation of average inhalation rates during active hours does not address the elevated breathing associated with various physical activities. Non-invasive monitoring of the respiration of randomly-selected individuals would provide useful information on breathing patterns during daily activities. The second approach offers some potential for yielding accurate, metabolically-consistent estimates of inhalation, provided that additional studies are completed with various age and gender cohorts using the doubly-labeled water technique for measuring metabolism. Despite the methodological differences between the first two approaches, they do yield comparable estimates of inhalation. The activity-based method suffers from problems associated with the recall of physical activities and the subsequent assignment of an appropriate MET value. This suggests that it might be better to use activity-based methods in conjunction with personal monitors that record pulse rate, which in turn can be related to oxygen uptake and respiration (see Griffiths and Payne 1976).

Inhalation rates used in dose assessments must be consistent with the energy expenditures of the target individuals/populations, and the most widely available estimates of energy expenditures in various countries are the food-energy intakes recorded in dietary studies. Moreover, such studies also provide the data for determining intakes of food items (e.g., leafy vegetables, milk, etc.) used in dose assessments. Although the inhalation methodology based on food-energy intakes is probably the most preferable approach from an assessment standpoint, it will still be necessary to make adjustments in the intakes of foods, beverages, and air to compensate for any biases associated with the particular dietary survey utilized. Another limitation in the use of dietary surveys for determining inhalation rates is that they only reflect the diet of a population for a particular time period, and thus such surveys may not be very useful in predicting future inhalation rates.

CONCLUSION

Many assessments of inhalation exposures to gases and particles over the past 15 years have relied on estimates of inhalation rates presented by Snyder et al. (1975) in ICRP Publication No. 23. The inhalation rates in that publication and in a newer analysis by Roy and Courtay (1991) are determined from ventilation rates for periods of rest and various physical activities. Unfortunately, breathing rates calculated in this manner are decoupled from the food-energy intakes needed to sustain the assumed activity levels. For example, an inhalation rate for adult males of 23 $m^3\ d^{-1}$ is equivalent to a caloric expenditure of about 17 MJ d^{-1} (4080 kcal d^{-1}), while an inhalation rate for women of 18 $m^3\ d^{-1}$ equals a caloric expenditure of nearly 13 MJ d^{-1} (3110 kcal d^{-1}). The equivalent caloric expenditure for men exceeds our adjusted caloric intakes/expenditures for adult males by a factor of about 1.4, and the value for women exceeds our estimate by a factor of 1.6. The principal source of the discrepancy between the energy-based approach presented in this paper and the TAV method is the estimation of inhalation during periods of "light" activity. For example, Roy and Courtay (1991) used a ventilation rate of 16 L min^{-1} for women conducting housework and 5.4 L min^{-1} during periods of rest. The ratio of the two inhalation rates is equivalent to a MET of about 3. This level of physical activity is not consistent with the sedentary nature of current U.S. lifestyles. In contrast, the average F or MET value in Table 5 is 1.5, which is the same value adopted by Sallis et al. (1985) to represent light activities. Because light activities represent about 60% of a days' physical activities, inaccuracies in the estimated breathing rate during this time have a major effect on predicted inhalation rates.

The principal ramification of using TAV-based inhalation rates in a dose assessment is the possible distortion of the inhalation route of exposure relative to ingestion—especially for radionuclides that occur in both food and air. In contrast to the activity-based approach for determining breathing rates, the approaches evaluated in this paper yield inhalation rates that are consistent with measured food-energy intakes and/or energy expenditures necessary to sustain reasonably energetic lifestyles. In addition, the methods presented to estimate inhalation rates can be used with other dietary studies to derive metabolically-consistent inhalation rates for dose assessments. Finally, a technique was developed for estimating the short-term inhalation rates based on the basal metabolic rate of an individual and the intensity of his or her physical activity.

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